GEOMORPHOLOGY OF THE MALLEE REGION IN SEMI-ARID NORTHERN VICTORIA AND WESTERN NEW SOUTH WALES

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ABSTRACT: A geomorphic map of the Mallee Region displays a variety of landforms characteristic of semi-arid southeastern Australia. Landform units have been identified primarily on a basis of the fluvial, lacustrine and aeolian processes that controlled them. Sand dunes constructed by prevailing westerly winds have extended from west to east in an area that includes the tributary junctions of the Murray-Darling system. Interference between aeolian and fluvial processes has combined to produce a complex network of terminal and groundwater lake basins which preserve the legacy of past changes in the hydrologic regime.

The construction of linear and irregular to sub-parabolic sand dunes and transverse clay-rich lunettes, previously dated as coinciding with the glacial maximum, is related to periods of major hydrological change. The origin of subdued linear forms with high clay and carbonate content involved deflation of sands, pelletal clays and carbonates from lower dune flanks and swales in a manner resembling that known to have occurred in the building of clay-rich lunettes. As well as controlling dune form, the original parent material, especially variations in the clay and carbonate content, may also have been responsible for affecting the varying degrees of rubefaction and consolidation evident between subdued linear forms and steep, high, irregular siliceous dunes.

In the southeastern region up to 2 m of fine grained sediment has been deposited as an airborne dust component derived during the building of the dunefields to the west.

Elliptical to sub-circular lunette lakes, in the regularity of their outlines, reflect the influence of surface water derived mainly from catchments outside the region. By contrast, irregular groundwater lakes with abundant coarse and fine grained gypsum (copi) occur in areic areas unconnected to surface drainage.

The scientific, educational and recreational importance of this region, located centrally to the large urban populations of southeastern Australia, demands that consideration be given to reserving large areas as parks or wilderness area; these may be allocated to multipurpose use in a way that ensures public access under suitable management.

INTRODUCTION

The physiographic province described in a general way by the term *Mallee* refers to those semi-arid plains of southeastern Australia characterized by extensive sand ridges on which eucalypts with a particular growth habit form the dominant cover. In these trees of relatively low stature, a cluster of branches emerges from a ligno tuber below ground level. From this specific connotation the term has come to describe entire regions where such eucalypts are common, the most extensive being the western portion of the Murray Basin extending from near Hillston in the north and Swan Hill in the south, west across the South Australian border to the Flinders Ranges.

This paper is concerned mainly to present a new map of the landforms of northwestern Victoria and southwestern New South Wales (Fig. 1). By integrating such evidence across the state boundary, we hope to provide a better understanding of this region, one that is as remarkable in the diversity of fluvial, aeolian and lacustrine landforms it preserves as in the complexity of Quaternary changes it records.

Few areas possess such a compact array of distinctively 'Australian' forms. A variety of continental dunes are represented in an area that includes the tributary junctions of southern Australia's main river systems. The Loddon, Wakool, Murrumbidgee and Darling Rivers all join

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the main Murray trunk stream within the boundaries of the map whilst the Anabranch of the Darling with its great chain of lake-lunette basins presents us with a fine example of forms peculiarly Australian. These major drainage lines converge within the region that once formed the most easterly extension of active desert dunes. The variety of processes thus involved have combined to produce a distinctive diversity of semi-arid landscape features. Since E. S. Hills drew attention to these features in 1939, we have only recently begun to comprehend the magnitude and complexity of the events involved in their formation. The map is designed to assist in that enterprise.

For many, the value of the map may lie more in the features it portrays than in the notes that accompany it. Therefore the comments which follow do not seek to provide a full and comprehensive account of the region but rather to describe some of the more salient points that underlie the logic of the land classification used, and contribute in a general way towards understanding the nature and the origin of the landforms depicted.

Previous surficial maps of this region have been confined to northwestern Victoria, notably the early description by Hills (1939), followed by the later land systems studies of Rowan and Downes (1963) and the geological investigations of Lawrence (1966). More recently Hills (1975) has re-examined the Mallee as a distinctive physiographic province. In its eastern part the map overlaps with the geomorphic map of the Riverine Plain (Butler *et al.* 1973). In the northwest the Darling river lakes have appeared on topographic and geologic maps of New South Wales (Geological Survey of N.S.W. — 1:250,000 series Manara and Menindee sheets). In producing this map we have drawn upon the evidence provided by earlier workers and have contributed new data principally from the New South Wales section. The boundaries chosen for the map are 141° and 144° east longitude and 32° and 36° south latitude giving a total area of some 115,000 km² (Fig. 2).

METHODS

Data were drawn from pre-existing maps, from photo-mosaics and from stereoscopic examination of aerial photographs checked by extensive ground traverses. An indication of map reliability is provided in Fig. 3. Information derived in this way was compiled initially at a scale of 1:250,000. In the process of reducing to final publication scale, a compilation was made at 1:500,000 identical with

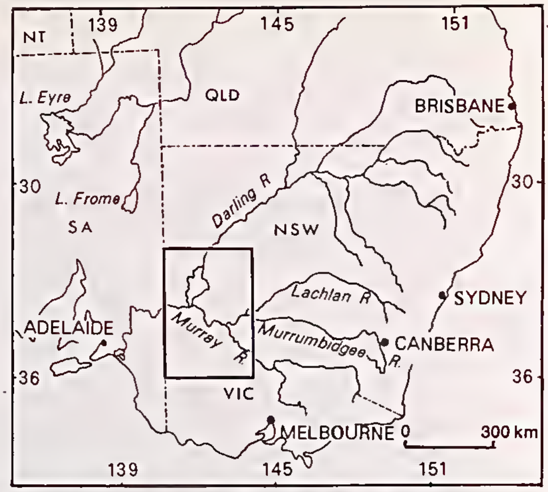


FIG. 2 — Location diagram. Inset shows area covered by Fig. 1.

that of the Geomorphic Map of the Riverine Plain (Butler *et al.* 1973). For research purposes this intermediate scale may prove more useful than the final publication at 1:1,000,000. Dyeline copies at the intermediate scale are available on request from the authors.

Classification and Mapping Criteria

The classification adopted in constructing the map is primarily a genetic one based on the distinctive expression of landforms of fluvial, aeolian and lacustrine origin. Such classifications based on mode of origin can rarely be applied with complete unambiguity. Throughout this region the characteristic expression of landforms related to specific processes reduces the dangers normally associated with a genetic classification. However problems occur in mapping areas of clay plain, the origin of which cannot be related specifically to any one process. Thus in the map legend two categories, namely *clay plain* and *clay plain with sand cover*, are not designated in terms of the processes that controlled them.

Seven aerial photographs are included to illustrate some characteristics of the geomorphic units mapped and examples of the variations which may occur within them.

GENERAL DESCRIPTION OF THE REGION

Geologic Setting

The present landforms and sediments which constitute the Mallee Region form the western portion of the Murray Basin of southeastern Australia. The sands and dunefields of Quaternary age overlie a predominantly marine sequence of Tertiary sediments (see Macumber 1978). To the

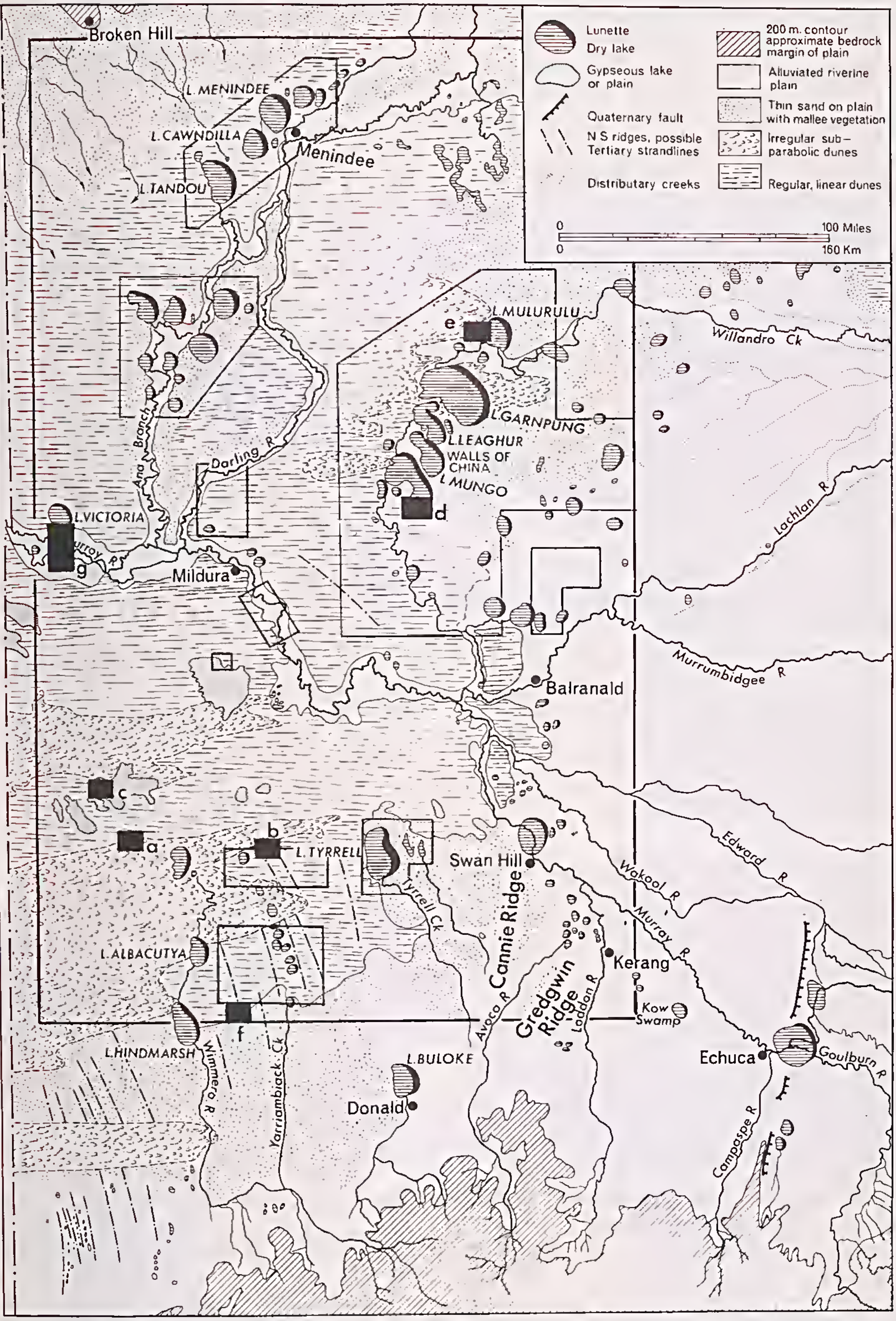


FIG. 3 — Regional map of Murray Basin. Large insets — areas examined by stereoscopic coverage. Small numbered insets — key to location of plates: a = Pl. 2(1), b = Pl. 2(2), c = Pl. 3(2), d = Pl. 3(1), e = Pl. 4(1), f = Pl. 4(2), g = Pl. 5.

east of the Mallee, the Riverine Plain of northern Victoria and southern N.S.W. (Butler *et al.* 1973, Pels 1969a, Lawrence 1976) forms the eastern portion of the Murray Basin. There too deposits of Quaternary age overlie Tertiary alluvial and lacustrine sediments.

The geological history of the Murray Basin has been summarized by Pels (1969a) and Lawrence (1976). A lower Tertiary marine transgression in the Murray Basin led to the deposition of calcareous sands, marls and limestones. A short regression was followed by an extensive transgression. During the subsequent regression in the upper Miocene to lower Pliocene a widespread, well sorted silt and fine to coarse grained quartz sand was deposited in littoral to near-shore conditions, the Parilla Sand of Firman (1965). On the surface of the Parilla Sand, a series of sub-parallel strandline ridges were formed as the sea retreated from the Basin (Blackburn 1962). These may be traced to the present coast in South Australia.

The Parilla Sands have had a marked influence on subsequent Quaternary sedimentation both as a source of sand for the aeolian units and as a structural control in that the sub-parallel north-south ridges control drainage lines and the distribution of lakes. Much of the inter-ridge laterized surface of the Parilla Sand is overlain by early Quaternary lacustrine sediments — the Blanchetown Clay and the Bungunnia Limestone (Firman 1965, Lawrence 1976).

Relief

The Mallee forms a broad plain interrupted by minor relief provided as dunes, channels or north-south ridges. Its elevation varies generally between 50 and 80 m above sea level with the southern portion, closer to the ranges, somewhat higher. Greatest relief contrast occurs in the northeast where the Manara Hills rise some 120 m above the Plain. The Darnick and Manfred Ranges are more subdued, emerging only 20 to 30 m. In the south the structurally controlled Cannie and Gredgwin ridges (Fig. 3) rise some 40 m above the dunefield but only 20 m above the adjacent clay plain.

Throughout the region lake basins are common, with depressions up to 10 m deep and adjacent lunettes rising 30 to 40 m above the plain on the larger examples. However on the numerous small basins lunette relief is usually less than 10 to 15 m.

The irregular, sub-parabolic dunefields have topographic relief with crests rising to 10 m above the regular dunefield in the north and up to 50 m in the Big Desert.

The NNW-SSE strandline ridges form subdued highs in the regular dunefields, commonly carrying lake depressions or river channels within the inter-ridge corridors. Where such ridges are buried by the sub-parabolic dunefield they tend to lose their topographic expression.

Climate

The Mallee Region lies on the southeastern margin of the arid zone and is characterised by a semi-arid climate, warm with moisture deficiency, in every season. Mean annual rainfall data are shown in Fig. 4. Precipitation decreases in amount and reliability towards the northwest. Rainfall distribution throughout the year is relatively even with a slight winter dominance in the south and equally small summer dominance in the north. Evaporation greatly exceeds precipitation; annual pan estimates increase from 1260 mm at Lake Boga in the southeast to 1640 mm at Menindee in the northwest.

Summer temperatures are high, commonly exceeding 40°C in January and February; winter temperatures are mild with maxima around 15-17°C and relatively low frost incidence at 5 to 15 days per year. Winds throughout the region reflect the dominance of the westerly system. Strong northerly and westerly components are represented throughout the year, with infrequent north-easterlies and easterlies. Dry northerly winds blowing from the arid continental interior sometimes produce severe summer dust storms, especially during periods of drought.

Vegetation

The vegetation of the Mallee Region is dominated by the eucalypt association from which it derives its name. This consists of low, multi-stemmed eucalypts (e.g. *E. oleosa*, *E. dumosa*) with shrubs and grasses. Where the regular dunefield becomes more open, with subdued relief, the fine grained swales carry fewer eucalypts with more grasses and other tree species, especially *Acacia*, *Casuarina*, *Hakea* and *Heterodendrum*. Stands of native pine, *Callitris* sp., are also frequent on some sandy areas.

The clay plains and lake floors tend to be treeless and are dominated by chenopodiaceous shrubs and grasses, with salt bush communities extending over large areas. River channels and flood plains are characterized by large eucalypt species, principally *E. camaldulensis* and *E. largiflorens*.

Throughout the region areas bare of vegetation due to development of scalds or blowouts are common, especially where intensive land-use has

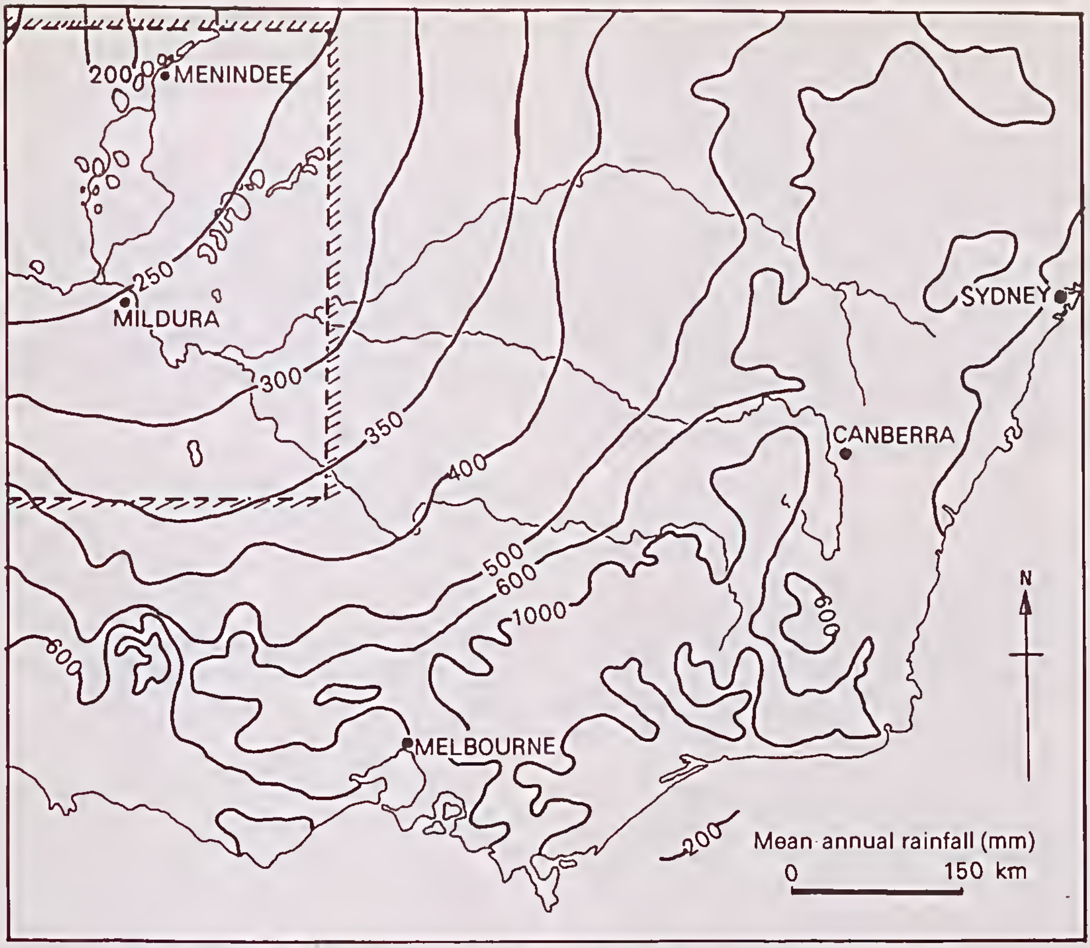


FIG. 4 — Map showing mean annual rainfall isohyets for southeastern Australia.

lead to widespread clearing of vegetation (Rowan & Downes 1963).

DESCRIPTION OF GEOMORPHIC UNITS

NORTH-SOUTH RIDGES

The presence of elongate ridges in the Victorian Mallee was recognized by Hills (1939) who showed their clear expression in contour patterns (Pl. 2(2) & 4(2)). On topographic maps the ridges are expressed as broad elongate features trending NNW-SSE as in the area east of Rainbow. Their presence is further emphasized on such maps by the complex channel network installed by the Victorian government during the depression years, to carry fresh water supplies from southern catchments to provide a reliable source to each landholder in the region. Many of the major channels run NNW. following the trend of the ridges (Pl. 4(2)).

Following soil surveys of similar features in the southeast of South Australia and southwestern Victoria, Blackburn (1962) postulated these ridges represented relict Tertiary shoreline features similar to those closer to the coast where the marine influence is clearly established. Although their exact manner of emplacement is not well understood, the ridges clearly represent successive strandline positions during retreat of the late Tertiary sea.

The map shows the occurrence of four ridges not previously defined in southwestern New South Wales. Although they are mainly covered by dense mallee eucalypt scrub the ridges are visible on mosaics and aerial photographs. The most prominent, north of Lake Benanee, has a broad flattish crest some 3 km wide that sweeps in a broad arc to the northwest.

Further inland the *en echelon* arrangement of the Willandra lake basins and the common NNW-SSE alignment of river channels may reflect the influence of similar structures now too subdued to be recognised in the topography. The presence of sediments resembling Parilla Sands in cores we obtained from 15-20 m beneath the floor of Lake Mungo together with outcrop there of silcrete cementing well sorted beach-like sands provides *prima facie* evidence that the limits of Tertiary transgression may have extended to the Willandra Lakes region. Indeed the easterly limit of quartz dunes in the southern region covered by the map lies close to the limits of marine transgression (Macumber 1969b). The marine sandy facies that underlies the core of the north-south ridges (Parilla Sands in the sense of Macumber 1969b, or Diapur Sandstone of Lawrence 1966) probably contributed a large component of source material to the linear dunes.

Drainage

The region demonstrates three types of drainage characteristic of arid and semi-arid environments. Firstly, throughout the greater part of the area, there is no contribution from surface runoff to overland flow. This areic aspect is reflected in the absence of channels from east and west of the Darling and from the entire area of northern Victoria north of Lake Tyrrell (Pl. 2(1) & 3(2)).

Secondly, the streams in the southern region, namely the Wimmera River, Yarriambiack, Tyrrell and Lalbert Creeks, which rise in the better watered hills to the south, are endoreic systems in that they lose their water as they flow north, and terminate in a string of lake basins amongst the Mallee sandhills (Hills 1975).

Thirdly, only the major rivers carrying waters from the wetter areas of the southeastern highlands and from southwestern Queensland succeed in crossing the plain (Pl. 5). Both the Murray and the Darling tend to lose water as they traverse the region to the west, a common feature of exoreic drainage in arid and semi-arid regions elsewhere.

Two additional aspects of the drainage are worthy of note. Firstly, the absence of lakes on the Darling River channel passing through Pooncarie is in marked contrast to the abundance of such features along the Anabranch channel. The fluvial stratigraphy, age and regime associated with anabranch formation upstream from Menindee is discussed elsewhere (Bowler *et al.* 1978).

Secondly, the dry channel of the Willandra Creek which wends its way through the field of linear dunes south of Outer Arumpo presents mute testimony of past hydrologic episodes in which the availability of surface water was much greater throughout the region than it is today. This channel last carried overflow discharge from the lakes some 16-18,000 years ago (Bowler 1971). Its preservation through the linear dunefields provides an excellent example of landscape longevity in this region.

Linear Dunes

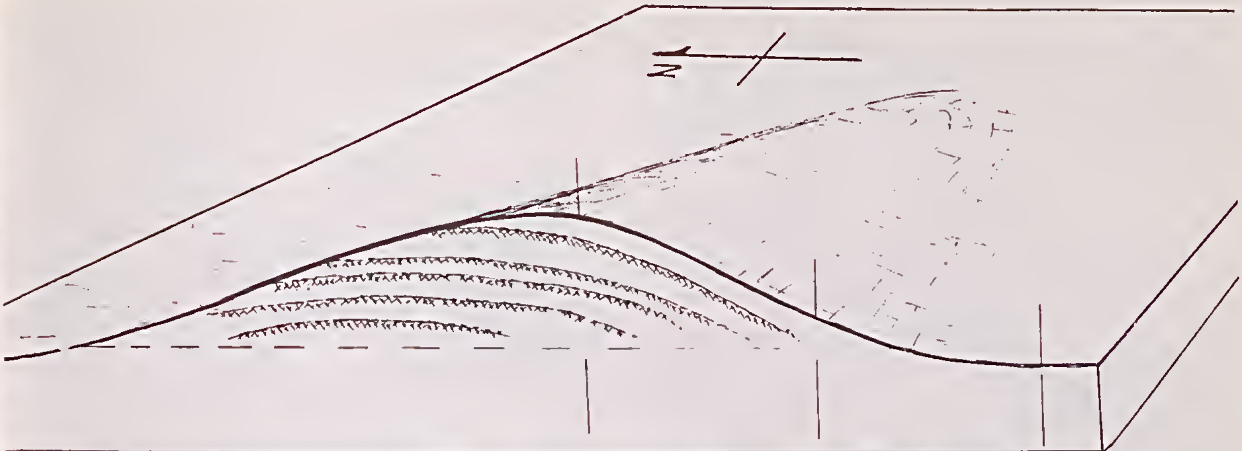
Low elongate sand ridges form the most characteristic landforms extending from north to south throughout the region. These dunes comprise relatively straight regular forms maintaining a west to east orientation reflecting the resultant direction of the controlling winds. In characteristic expression such as west of Swan Hill (Pl. 2(1) & (2)) they maintain a relatively uniform spacing from 0.2 to 1.2 km apart, varying in length from 0.5 to 3 km, but typically about 1.5 km long.

In section, the dunes possess low, rounded, subdued crests rising usually 2 to 6 m above the swales with occasional relief to 10 m. The slopes are gentle, with the south-facing side usually steeper, producing a slightly asymmetric cross-section (Hills 1939, Churchward 1963) as illustrated in Fig. 5. Sediments forming the dunes constitute the Woorinen Formation of Lawrence (1966).

In their composition the linear dunes contain a relatively high percentage of clay and calcium carbonate. Studies by Churchward in the southern region northwest of Swan Hill record clay values commonly reaching 20%, with an average composition of about 7-10% within dunes but reaching higher values in swales (Fig. 5). Carbonate in the same region varies from peak values of 14% in the uppermost (Kyalite) layer to an average composition of about 5% (Churchward 1963). The carbonate content which remains relatively high throughout the linear dunes of northwestern Victoria diminishes to the north through New South Wales, although the clay component remains relatively high throughout.

From crest to swale the linear dunes display strong catenary development. Clay and carbonate content increase down slope reaching maximum values within the swales where fine grained clay loam is often associated with a carbonate pan or calcrete. This catenary development contributes to the characteristic expression of the linear dunes in which the low, subdued forms with rounded ends appear to rise like submarines partly submerged in a sea of fine grained sediment (Fig. 5). This impression is enhanced by the selective colonization of the well drained crests by mallee eucalypts with more open grassland developed on the fine grained swales.

In vertical section the linear dunes throughout the southern half of the region contain a series of



DEPTH	Clay	$CaCO_3$	Clay	$CaCO_3$	Clay	$CaCO_3$
0–50cm	5	1	15	1	17	3
50–100cm	16	4	25	20	29	36

FIG. 5 — Perspective diagram showing relationship of internal soil horizons to form of subdued linear dune. Geometry of buried soil horizons (not necessarily groundsurfaces), extrapolated from photograph of Nyah West railway cutting. Analyses refer to catenary data; the two sets of figures refer to percentage clay and carbonate respectively on crestal, midslope and swale sites. Profile data generalised after Rowan and Downes (1963) and Churchward (1963).

calcareous paleosols (Hills 1939, Churchward 1961) indicating a long history throughout which the dune form has been perpetuated during each successive phase of aeolian reactivation (Fig. 5). Stratigraphic studies of the buried soils suggest that the last major phase of dune growth occurred some 15,000 years ago (Bowler & Polach 1971), following a long period of stability during which a previous paleosol had formed (the *Speewa* of Churchward 1961).

Virtually all the linear dunes are relict features which were stabilized by thick vegetation cover until the time of European development. Some have been reactivated, especially where the clearance of the Mallee woodland was followed by long droughts as in the 1930s, during which cultivation resulted in widespread sand mobilization. The redeposited layer often forms a thin blanket across the dune surface, a layer that corresponds to the *Piangil* of Churchward (1961).

A variation of the regular longitudinal dunes occurs near the boundary between linear and irregular, sub-parabolic dunes; it forms a transitional phase between the two groups. Such dunes are found west of Outer Arumpo and south of the Sunset Desert where long sharp-crested, siliceous dunes maintain regular linear forms for more than 5 km (Pl. 3(2)). In contrast to the typical low rounded dunes, they are higher, more closely spaced and maintain a well sorted sand texture from crest to swale; the catenary transition from coarse to fine is lacking. Moreover the preservation of steep, sharp crests indicates the development of sand-slip faces during mobilization, a feature that is significantly absent from the subdued linear forms.

IRREGULAR, SUB-PARABOLIC DUNES

Large fields of steep, irregular siliceous sand dunes extend as elongate west to east lobes particularly well developed in northwestern Victoria and east of the Darling River in New South Wales. Within such areas a wide variety of forms is represented. Although generally more irregular than the linear varieties they often transgress, and sometimes referred to as 'jumbled' dunes, they possess a degree of order reflecting the influence of the prevailing westerlies which formed them (Fig. 6). Thus east of Lake Garnpung closely spaced parabolic forms, interfering with each other and resulting in irregular or sub-parabolic outlines, are oriented with their apexes pointing east. Within the Sunset and Big Desert regions, the plan geometry of dune crests is less regular but even here the influence of the westerly vector finds expression (Pl. 2(1) & (2)).

Within this group of irregular and sub-parabolic forms, crests frequently rise more than 10 m above swales. Slopes are steep and crest to crest distances

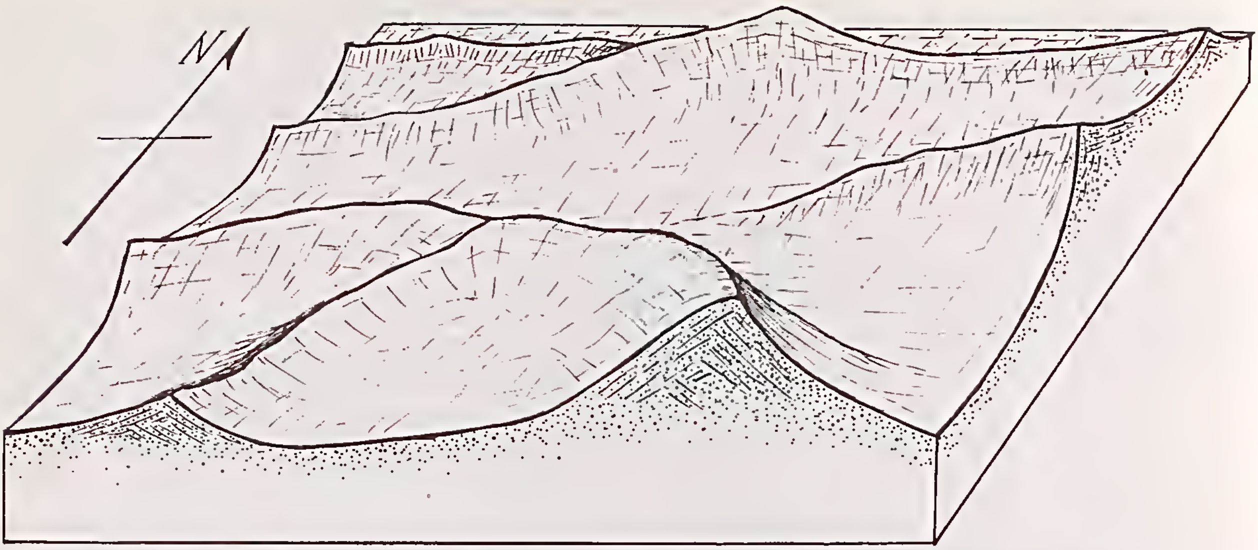


FIG. 6 — Idealised perspective diagram (without mallee scrub cover) through irregular to sub-parabolic dunes showing relationship between form and internal structure. Deep siliceous quartz sands average about 2-3% clay with 0.5% carbonate according to Rowan and Downes (1963).

are extremely variable, though dune spacing is much closer than in the open, linear forms.

Sediments of the sub-parabolic sand dunes are highly siliceous. Carbonate is usually absent; when present it occurs only in minor amounts sometimes as soft chalky elongate concretions developed after tree roots. Similarly the high percentage of clay which characterizes the catenary profile of the linear forms is absent from the sub-parabolics; in these the profile from crest to swale consists of relatively uniform siliceous sand (Fig. 6).

SAND PLAIN

Areas designated as sand plains occur as two distinctive and widely separated areas. In the northeastern sector (Pl. 4(1)) and in a discontinuous belt following the Darling River and the Anabranch, an undulating sand plain is characterized by irregular sand accumulations equivalent to the hummocks of Rowan and Downes (1963). These are sub-circular in plan, occurring commonly as a complex of mounds varying from less than 100 m to 3 km in diameter and from a few metres to over 30 m in elevation. Hummocks are formed from a variety of materials ranging from sands to sandy clays with evidence of layered paleosols and catenary profile differentiation (Rowan & Downes 1963).

The second area mapped as sand plain occurs in the southeastern corner lying on either side of the Avoca channel, forming the surface expressions of the Gredgwin and Cannie ridges (Fig. 3). Macumber (1969b) has demonstrated the presence there of Tertiary marine sandstone bounded on the east by a north-south fault with uplift on the west. There are certain difficulties in including these areas in the sand plain category in that their surficial materials combine components both of sand and finer clay loam. But they are included rather than establish an additional unit.

LUNETTE

This region includes some of the best examples of lunettes to be found in Australia. Indeed, in first defining such features from northern Victoria, Hills (1939, 1940) drew heavily on his experience of Mallee examples.

Their occurrence as smooth, crescentic, transverse dunes on the eastern side of lake basins (Pl. 3 (1)) is well known from other parts of southern Australia. They record complex oscillations of past hydrologic sequences varying through periods when deep and relatively fresh water concentrated clean quartz sands on eastern beaches for contribution into the down-wind dune. Later, during more saline conditions associated with drying, gypseous clay pellets were transported by saltation from exposed lake floors to provide the smooth surfaces most characteristic of their present form (Bowler 1973).

The size of the lunette generally bears a strong relationship to the size of the basin from which its materials were derived. Thus on small lakes less than 1 km in diameter, the lunette may be only a few metres high, whereas on larger basins they frequently rise to more than 15 m; they reach to 30 m above the lake floor on the Chibnalwood Lakes on the Willandra Creek and to 40 m on Lake Tyrrell.

Lunettes are often composed of multiple stratigraphic units. On some lakes these are laterally separated from each other (Pl. 3(1)), producing a concentric system as on many of the Darling River lakes and on Lake Tyrrell and Lake Albacutya. On others the units are superimposed vertically, one on top of the other, to produce a single complex ridge such as on Lake Mungo and Lake Tutchewop.

Lunettes throughout this region are exclusively relict features relating to hydrologic events of late Pleistocene time. Dates available from the last episode of lunette building cluster in the range between 19,000 and 15,000 B.P. with many showing evidence of synchronous development between 17,000 and 16,000 as at the Willandra Lakes, Tysons Lake and Lake Albacutya (Bowler 1976).

The sediments that comprise these features are closely related to the hydrologic conditions that formed them. Those that occur in close proximity to major drainage channels tend to be dominated by deep, freshwater facies which contributed large quantities of quartz sand to the shoreline dune. Thus the lunette on Travellers Lake on the Darling River consists entirely of quartz sand, suggesting this basin never experienced the hypersaline environment necessary for the formation of the clay-rich lunette materials. Others such as the Chibnalwood Lakes (Pl. 3(1)), Lake Tutchewop and Lake Albacutya contain relatively high percentages of gypsum in their upper units, consistent with their final stage development having taken place under saline conditions.

Stratigraphic and chronologic analysis of lunettes has been particularly instructive in helping demonstrate the complex palaeohydrologic history, the legacy of which is preserved in the landforms of this region (Bowler 1971, 1973, Macumber 1970, Gill 1973). Moreover the lunettes provide a most favourable environment for the rapid burial and preservation of archaeological remains relating to periods when early Man camped on the shores of the predominantly freshwater lakes. Lunettes throughout this region have provided one of the richest sources for the evidence of prehistoric Man and vertebrate remains in southern Australia. Sites such as Menindee, Tandou, Nitchie, Lake Victoria, and the variety of Willandra sites centred on Lake Mungo have become hallmarks in the literature of Australian prehistory. Furthermore the archaeological potential and faunal content of lunette sites have only just begun to be adequately explored. In future studies, the, lunette lakes of the Mallee Region will continue to yield much new information.

Lake Floors

Lake basins have been represented on the map where the presence of lowlying areas is defined by a relatively sharp break in slope on the western margin representing an ancient or modern cliff line (Pl. 3(1) & 4(1)). On their eastern side such depressions are enclosed by lunettes so characteristic of lake basins across southern Australia. The basins are typically smooth and elliptical, often kidney-shaped in outline, with the long axis oriented N.-S. or NNW.-SSE.

All large basins are associated with drainage lines which contributed the surface waters so important in shaping their outlines. Thus the Murray River has groups of lunette lakes marginal to its channel as at Robinvale, Hattah and Lake Victoria (Pl. 5). Similarly the numerous lakes of the Anabranch and the Willandra Creek owe their characteristics to past high stage surface flows of the Darling and Lachlan Rivers respectively. Other large lunette basins such as Lake Tyrrell and Lake Albacutya occur as terminal systems of the Tyrrell Creek and Wimmera River. The numerous basins near Hatfield and Balranald occupying regions where no surface water is available today represent a legacy of past environments that were much wetter than the present climate, at least in terms of runoff if not in absolute precipitation.

Most lake basins are dry, although some are filled artificially for use as water storage basins. Two types of such use are involved: one for the storage of freshwater as at Menindee, Kangaroo Lake and Lake Charm near Kerang; secondly, some are now being used as evaporation disposal basins for saline groundwater as at Lake Tutchewop and in a scheme presently being considered by the State Rivers and Water Supply Commission of Victoria for Lake Tyrrell.

Some lakes, such as those on the Darling River, are filled by ephemeral flooding. These drain back into the river attenuating the passage of the flood wave. Others, such as Lake Tyrrell, intersect groundwater systems. With its characteristic salt encrusted surface Lake Tyrrell forms the largest salt lake in Victoria.

Sediments on the floors of most dry basins consist exclusively of fine grained materials dominated by clays, with silts and sands more prominent on the eastern downwind margins. The clay plains sometimes possess large desiccation cracks where montmorillonite forms a substantial component in the clay mineral assemblage. Exchangeable salts remain high; this is reflected in the nature of the salt tolerant vegetation that colonizes the lake floors. Where the floors have been modified substantially by later alluviation or other processes they are shown on the map as alluvial or clay plain units.

The western margins of the basins frequently truncate the easterly extension of linear or irregular dunes. Rarely do such dunes transgress onto the lake floors, a phenomenon which Bowler (1971) attributed to the presence of water in the lakes simultaneously with the advance of the dunes. Exceptions occur in the Willandra Lakes where lobes of irregular dunes transgress across the ancient shorelines of Lake Garnpung and Outer Arumpo (Bowler 1971). In the southern portion of the map, some lunette lakes are apparently submerged beneath transgressive dunes of the Big Desert along the course of Yarriambiack Creek, providing a rare example of dune encroachment across lake floors.

Gypseous Lake Floor or Plain

Landforms of this category occur in the most northwesterly sector of Victoria, north of the Big Desert, and in N.S.W. west of the Anabranch. The occurrence of gypseous deposits indicates that in the past these low lying areas have been sites of groundwater evaporation. They are characterized by asymmetrical irregular shapes (Pl. 3(2)) in contrast to the lunette basins where abundant surface water has helped produce smooth symmetrical outlines. Furthermore on aerial photographs the surface within the depression rim possesses irregular convolute patterns, often with a north-south orientation (Pl. 3(2)). These in part reflect past wind sculpturing of gypseous material on the floors of areas such as the Raak Plain where gypsum is mined commercially. Low aeolian ridges of white fine grained gypsum (copi) are common.

The occurrence of irregular gypseous and elliptical lunettes lakes are mutually exclusive. Thus, in northern Victoria, an east-west line from Ouyen to Murrayville effectively separates the irregular gypseous basins in the north from the regular elliptical lunette basins in the south. The same line also forms a boundary between areas of no surface drainage and the terminal drainage systems of the Wimmera, Yarriambiack, Tyrrell and Lalbert Creeks with which many lunette lakes are associated. The gypseous lakes on the other hand occur in regions remote from drainage lines, where the hydrologic contribution was restricted in the past as it is today to local runoff and especially to groundwater inflow.

Upper Alluvium

In the area adjacent to the Darling-Murray junction a sequence of alluvial terraces is inset below the general level of the aeolian plain. The upper terrace lying above the general level of flooding is designated upper alluvium (Pl. 5). It corresponds to the Neds Corner Land System of Rowan and Downes (1963) and extends up the tributary system of the Darling and Anabranch channels. Although it is present in the Murray Valley upstream from Mildura it has not been identified at the mapping scale. This unit is inset into, and therefore postdates, the inception of the linear dunefield. Whilst the surface cover of sand and clay may in part be aeolian, the sediments comprising this terrace are dominantly fluviatile. Near Mildura, the unit possesses a calcareous red brown earth soil and is in part equivalent to the Green Gully ancestral river phase further upstream in the Murray Valley. However, since we are not able to differentiate between all terrace levels within the alluvial belt, this unit should not be taken to indicate chronologic continuity. The unit as mapped includes alluvial sediments of different ages.

Lower Alluvium

This unit which follows the major drainage channels throughout the region is generally equivalent to the modern floodplain. Downstream from Wentworth it maintains a relatively constant level below the higher level designated as upper alluvium (Pl. 5).

Soils developed on the sandy loams of this system are generally grey acidic profiles equivalent to the minimal prairie soils described by Butler (1958). The unit represents the stratigraphic equivalents of the youngest ancestral river phases of Pels (1969b). The large areas designated as lower alluvium upstream from the Walkool Junction almost certainly include areas of older alluvial deposits, areas unable to be differentiated at the mapping scale adopted. Moreover in the same region the differentiation between alluvial clay and clay plain of undesignated origin remains somewhat arbitrary, but wherever surface drainage patterns show the influence of overland flow and associated deposition these plains have been classified as alluvial.

Clay Plain and Clay Plain with Sand Cover

Within the map categories, two groups of non-genetic origin have been specified, clay plains and clay plains with sand cover. Since the latter constitute a slightly modified version of the former, discussion of their distribution and significance may usefully be considered together. Lying east of the dunefields they constitute large areas between major drainage lines. On the Geomorphic Map of the Riverine Plain, the clay plains east of Sea Lake are shown as 'dominantly of aeolian origin' by Butler *et al.* (1973). Whilst the surface sand cover is demonstrably reworked by wind, the origin of the extensive surface clay of the wheatlands region in the southeast of the map remains in doubt. The relative contribution of sediment from former lacustrine, fluvial or aeoloian episodes is not known.

This unit corresponds generally to the Culgoa Land System of Rowan and Downes (1963). The clay plains, often with the strong development of gilgai, originally carried a cover of eucalypt scrub. This has now been cleared throughout most of the region for grazing and cultivation.

The clay plain with sand cover represents a unit of restricted extent transitional between clay plains and linear dunefields. Its boundaries in the southeast are clearly related to the topographic expression of the north-south ridges (Pl. 4(2)).

Bedrock Hills

Pre-Tertiary outcrops occur in the northwest of the region where the Manara, Darnick and Manfred Ranges form inliers of Upper Devonian sandstone protruding through the Tertiary and Quaternary cover. These form stony ranges rising above the surrounding plain. Tertiary erosion of these and similar rocks probably contributed substantially towards the supply of quartz sands that now mantle the greater part of the plains surrounding them.

DISCUSSION

Origin of Dune Forms

a. *Linear dunes*. Variations in the form, sediments and stratigraphy of the different dune types help provide clues concerning their origins. This is particularly relevant in the case of the subdued linear dunes formerly regarded as being degraded remnants of once larger, steeper forms. Within such dunes (Fig. 5) successive layers separated by buried soils indicate the retention of form similar to that of the present day despite successive episodes of re-mobilization (Hills 1939, Churchward 1961). Moreover the abundance of clay and carbonate within their soil profiles even on crestal sites suggests that new layers added during arid episodes were derived from fine-grained calcareous sediment in the swales as suggested by Rowan and Downes (1963). This is confirmed by the presence of sand-sized clay aggregates observed in thin-sections we have examined through such a dune at Nyah West. The aggregates bear a resemblance to some developed on salinized depressions, the importance of which has been documented for lunette formation (Macumber 1970, Bowler 1973). The extent to which they have resulted from normal erosion of pre-existing soils or were assisted by saline efflorescence on flanks and swales cannot be ascertained. However, the presence of clay pellets preserving traces of original depositional fabric implies an important relationship with the clay lunette forming processes.

This phenomenon is consistent with the age postulated for the last episode of linear dune mobilization believed to lie between 25,000 and 16,000 B.P., an episode that followed a wet period in which watertables and lakes were considerably higher than today (Bowler *et al.* 1976). With a reversal of the hydrologic budget towards drier conditions groundwater salts would have accumulated in the swales where abundant surface water would previously have produced downward leaching. With decreased runoff, swales and lower dune flanks may have become sites of groundwater or soilwater evaporation loss. Any salts thus concentrated would have contributed to the development of carbonate pans and to the efflorescence responsible for breaking clays into pellet sized aggregates for deflation onto the flanks and crests of the adjacent dunes.

One further line of evidence supports this notion of dune growth. Each successive aeolian unit was deposited in approximately conformable attitude across the pre-existing topography. Although individual bedding planes are not preserved, this structure is strongly suggestive of the laminar subhorizontal bedding so frequently found within clay-rich lunettes (Bowler 1973). Dune growth by mobilization under the influence of steep migrating sand-slip faces would have produced aeolian units of variable thickness and with sharpened crests. The absence of such features reflects initial growth patterns rather than subsequent degradation. Thus the accretion process resembles the formation of the transverse clay-rich lunettes which, throughout this region, were actively forming simultaneously with associated longitudinal dunes in the interval centred on the period between 17,500 and 16,000 B.P. (Bowler *et al.* 1976).

Throughout the remobilization process pre-existing linear dunes remained bonded by compact clay and calcareous soil horizons. Not only did the form remain stable with the younger layer draped slightly asymmetrically over the central axis but no significant downwind migration of individual dunes occurred. Thus they have remained short and occur at relatively constant spacing despite a long history throughout late Quaternary time. Unlike the more mobile linear forms of Central Australia they never form Y-junctions, a feature attributed here to their unusual composition and the manner of formation it reflects.

This proposed mechanism of formation can be tested in several ways. Firstly, subdued linear dunes, if formed as a result of salinization after a period of high watertables, will not be found on well drained parts of the landscape. Their absence from the Cannie and Gredgwin ridges may indeed be due to this factor. Secondly, unlike the quartz dunes of the Simpson Desert (Twidale 1972) their regularity will not vary downwind from stream channels. Since their source materials are derived from adjacent swales rather than channel sands, the relative constancy of length and spacing will not vary on either side of intersecting channels. Thus there is no change in the distribution or shape of dunes east and west of the Willandra channel south of Chibnalwood Lakes, a feature that stands in marked contrast to the change in geometry of linear Simpson Desert dunes north and south of the Finke River in Central Australia.

Thus a number of apparently anomalous aspects of the linear Mallee dunes are explained by this mechanism. Their smooth subdued expression represents a depositional influence. The formation of longitudinal dunes by the mechanism proposed here involving salinization of swales has not previously been recorded from Australia, nor are we aware of examples from other arid regions. In this respect they constitute a group of particular interest related to transverse clay-rich lunettes.

b. *Irregular sub-parabolic dunes*. In areas of the sub-parabolic, irregular dunes, neither carbonate nor clay was incorporated into the original parent material; the final expression is markedly different from dunes where such materials were present. Despite the long interval that has elapsed since the last period of mobilization the irrregular and sub-parabolic forms retain their sharpened crests and steep slopes reflecting active crest migration and the development of avalanche sand-slip faces during their formation (Fig. 6). Moreover when mobilized, siliceous dunes involved much larger quantities of quartz sand than is found in the linear forms. The occurrences seem to be dependent on the availability of a large sand supply free of bonding clay and carbonate. Their tendency to occur on the eastern side of alluvial or lacustrine depositional areas represents a further expression of this relationship between form and large sand supply.

Where dated with respect to lacustrine events in the Willandra lakes, two large lobes of irregular dunes were actively advancing on Lakes Garnpung and Outer Arumpo when these lakes were drying between 17,500 and 16,000 B.P. In Victoria, dunes of the Big Desert encroached onto the western shores of Lake Albacutya where radiocarbon dates suggest it too was building its last lunette about 16,000 B.P. (Bowler 1976). Moreover the overflow channel to the north, Outlet Creek, was kept open through the dunefield, suggesting that, as in the Willandra lakes, seasonally high runoff was sufficient to counteract dune movement during this active phase. Thus the last active development of Big Desert dunes occurred synchronously with mobilization of the siliceous dunefield east of the Darling River, an event that coincided with the last glacial maximum about 18,000 to 16,000 years ago.

c. *Vegetation influence*. An additional factor affecting the mobilization and final geometry of dune form concerns the nature of vegetation cover at the time of mobilization. In the case of linear dunes the deposition of a relatively thin blanket of calcareous clayey sand over the pre-existing form suggests that some vegetation cover was retained even whilst the new materials were accumulating. The retention of grasses or low shrubs would be consistent with the stratigraphy of aeolian units and the absence of bedding in such deposits. On the other hand, the formation of irregular dunes involved the destruction of all pre-existing soil profiles from crest to swale, demonstrating a degree of mobilization much in excess of that typified by linear forms. It implies almost complete if not total destruction of vegetation. Thus any factor that effectively destroys vegetation across large areas will be more conducive to the formation of irregular siliceous dunefields.

The lobes that extend to the east downwind of Lake Garnpung and Lake Mungo may owe their origin to a combination of two factors. Firstly, they may have been assisted by increased availability of quartz sand on the downwind side of the lakes. Secondly, the effect of salts derived by deflation from the drying lake floors contemporaneously with the building of the saline lunettes would have assisted in the destruction of vegetation downwind. This in turn would lead to accelerated erosion and more complete mobilization of pre-existing dunes from crest to swale.

The high, sharp-crested, siliceous variation of the regular linear dunes described earlier (Pl. 3(2)) is related by composition and genesis more closely to the irregular, sub-parabolic forms than to subdued, clay-rich calcareous dunes. The same type of deep sand mobilization with downwind migration of the forms as described for the irregular forms, applies also to the transitional linear forms.

With progressive excavation of swales and additions to crests, dunes will interfere with each other, with consequent reduction of regularity and frequent formation of Y-junctions (Pl. 3(2)).

Colour of Dune Sands

The characteristic colour of sands throughout most of the region is reddish brown (2.5 YR 4/8). In sections through dunes this varies through different pale shades depending on the percentage and distribution of carbonate. However in both the Big Desert and Sunset Desert the siliceous dunes consist of pale yellow to whitish sands in contrast to the reddish dunes they sometimes transgress.

In considering the origin and significance of the red colouration two observations are pertinent. Firstly, wherever dunes can be observed to have taken up the red colour *in situ*, as in source-bordering river dunes, a gradation exists from the surface downwards to progressively paler shades in the parent sands. When seen in thin-section, the rubefaction is due to the development of a clay-rich cutan coating the quartz grains. The clay rim becomes progressively more oxidized to a ferric state in the higher parts of the profile. Secondly, wherever a succession of such dunes exists, as on ancestral rivers and prior streams of the Riverine Plain, the degree of cutan and oxidation development increases with age; the older dunes are reddest and possess the deepest profiles.

The reddening of the sands throughout the Mallee region is seen as a cumulative pedogenic effect inherited over the many thousands of years since the quartz grains were originally deposited by fluvial, marine or lacustrine processes. During each stage of soil erosion and redeposition the red cutan is retained, although at times it undergoes considerable abrasion. However, once a grain has acquired its red iron-rich clay coating, it will usually retain sufficient of it to impart a reddish translucent hue. When such dunes are blown into a river or into a lake and subjected there to rolling and wave action, the grains are rapidly stripped of their red coatings. They may emerge on the downwind banks or beaches as clean white sands with only occasional traces of red staining.

Following this line of evidence, the origin of the whitish sands in the large irregular lobes that transgress from South Australia into Victoria may be a function of the following factors.

Firstly, if the sands consisted originally of pure quartz there may have been insufficient clay to form the cutan in which haematitic iron is located. But it may be argued that given sufficient time all quartz dunes would eventually turn red, an argument that is not entirely supported by the persistence of pale colours in dunes of Saharan Africa and Saudi Arabia.

Secondly, such dunes lacking clay and carbonate are most susceptible to erosion and re-mobilization. They have probably been active more frequently and for longer periods than other dunes in the area. Thus they have never been stable for sufficient time to develop distinctive pedogenic horizons.

In the area west of Outer Arumpo Lake regular linear dunes pass progressively into steep, less regular siliceous forms. Here there appears to have been an evolution through stable linear forms, with sufficient clay to produce effective pedogenesis, to totally mobilized forms from which the clay has been removed during deflation. Unlike the Victorian irregular dunes, a strong reddish colour is characteristic of the irregular dunes between the Darling River and Willandra lakes. This represents an inherited feature of past more stable conditions. Conversely the absence of rubefaction in the irregular lobes of Victoria may reflect a combination of initially low clay content and periods of stability too brief to permit pedogenic rubefaction to take place.

Aeolian Clay

The problem concerning the origin of the clay plains has already been referred to. Lying on the downwind side of dunefields they almost certainly contain a significant component of wind-blown clay and fine sand derived during the long period available for the accession of airborne dust. Although mapped previously as 'parna' (Rowan & Downes 1963) the magnitude of dust accession in the composition of the plains remains unconfirmed.

Some indication of the depth and characteristics of aeolian clays in this region can be ascertained from examination of sediments that cap the Gredgwin Ridge. Its upper level lies well above the influence of fluvial or lacustrine deposition. Within the quarry studied by Macumber (1969a) upper Tertiary silicified and ferruginous sandstone is overlain by 2 m of reddish sandy clay which we have examined in thin-section. Assuming relief of the block dates from soon after regression of the Tertiary sea, the upper clay-rich unit can only have been derived either by weathering of underlying sediment or from airborne dust from areas further west. In a profile from this quarry the mineralogic and weathering characteristics of the upper 1.5 m demonstrates that it is genetically distinct from the underlying sands. Moreover the upper clay-rich and basal marine sand units are separated from each other by a major weathering disconformity. At the contact, translocation of iron and silica has produced extensive ferric iron concretions and nodules associated with secondary opaline silica.

Therefore the surficial clay cover represents a later accumulation and is best explained by aeolian deposition of fine grained material from suspension (*parna* of Butler 1956) equivalent to the various aeolian episodes recognised within the linear dunes to the west. The clays contain a high percentage of silt-size quartz with characteristic ferric iron-rich kaolinitic cutans similar to Wüstenquarz grains derived from desert dusts, a feature that reinforces evidence for an aeolian origin.

Assuming that the dust component once lodged on the Gredgwin surface was not removed by later deflation, the evidence points to deposition of up to 2 m of fine grained sediment equivalent in time to the growth of the linear dunes. However, on the clay plains to the west of the Gredgwin and Cannie ridges fine grained deposits often exceed 2 m, suggesting that other depositional processes in addition to aeolian activity have been involved in their origin.

Land-use and Recreational Activities

Ample statements are to be found elsewhere of the impact of Man in this landscape, where a delicate balance exists between its ecosystems, landform stability, hydrology and climate. A slight disturbance in one is sufficient to cause drastic and perhaps irreversible changes in the other. The effects of vegetation clearance and irrigation, with consequent and widespread increases in salinization, are just some examples. It is not our intention to summarize the various practices of dry land and irrigation farming that have been developed within this region. However, in addition to the predominantly agricultural economy there is one aspect of land-use whose importance and impact will accelerate dramatically in future years. This concerns tourist, recreational and educational activities.

The Willandra Lakes lie near the centre of a circle, on the circumference of which lie the great urban centres of Adelaide, Melbourne and Sydney. Landholders in the Willandra area, within this once forgotten quarter of western New South Wales, are now being awakened to the reality that half Australia's population lives within just one day's drive of them. The invasion of sightseers, tourists, school tours and other elements more destructive to fauna and flora has increased dramatically in recent years. Already the State authorities have recognized the necessity to cater for these activities, the intensity of which will increase exponentially as urbanized society becomes increasingly more disenchanted with its environment. The existence of National Parks at Menindee (Kinchega), Hattah Lakes and Wyperfeld are tangible expressions of the States' concerns. However, given the marginal economic viability of both dry land grazing over large areas in the Western Division of New South Wales and similar reservations about the value of irrigation with its irremedial side effects on both sides of the border, serious consideration should be given to declaring large tracts both north and south of the Murray as protected wilderness areas. In Victoria, Lake Tyrrell, the largest salt lake in the state, together with sections of the Sunset and Big Deserts should be considered. In New South Wales consideration for protection of the Willandra Lakes is already in progress. Additional areas might include large tracts of relatively undisturbed mallee dunefields including part of the permanent drainage of either the Darling River or the Darling Anabranch near Travellers Lake; Lake Victoria with its proven scientific potential might also be so protected.

Whilst we acknowledge the financial problems this involves for State authorities and the possible inconvenience to present landholders, the long term needs of the Australian community demand that representative portions of this region with its scientific, aesthetic and recreational value be protected for future generations.

CONCLUSIONS

The geomorphic map of the Mallee region demonstrates a variety of aeolian, lacustrine and fluvial landforms that are distinctively 'Australian' in character. The record of past environments extends back to late Tertiary time when the NW.-SE. trending ridges were built as successive strandlines during final retreat of the Tertiary sea. Today the ridges often control the course of drainage lines and the location of terminal lakes.

The area is dominated by a variety of dune forms almost all of which are now vegetated. Thus the subdued linear dunes, the irregular lobes of large sub-parabolic dunes and the lake-shore transverse lunettes preserve the legacy of Quaternary environments when aeolian activity was much greater than it is today. Similarly the two varieties of lakes, the elliptical lunette lakes and irregular gypseous groundwater lakes, in their shoreline features and associated aeolian sediments, reflect alternating periods when both groundwater and surface water supplies were sometimes in excess of, and at other times, less than those of today's regime. In this respect the Mallee region will continue to prove a fruitful area for studies of Quaternary environments, a context that will continue to tell us more of early Man and of changing flora and fauna in this continent.

Earlier studies established that whilst several phases of lunette development are evident on many lake basins throughout the region, the last lunettes were built about 18,000 to 16,000 B.P., simultaneously with the maximum extent of global glaciation. At the same time both linear and transgressive sub-parabolic dunes were reactivated.

The mechanism by which regular, subdued linear dunes were formed, with high clay and carbonate content, involved deflation of sediments from adjacent flanks and swales. The dunes accumulated layer by layer over the pre-existing topography. They did not form mobile sand-slip faces nor did the forms migrate significantly downwind. The presence within their sediments of pelletal clay aggregates suggests a mechanism of formation resembling that documented for transverse clay-rich lunettes. In this process, salinization of swales following the long period of high watertables that existed before 25,000 B.P. may have played an important part in destroying vegetation and in breaking up calcareous clays and sands by effloresence of salts; the pellets and sands then formed blanket deposits on adjacent dunes. The shapes preserved today closely resemble the original depositional form; they are not degraded remnants of once larger features.

Variations in form and colour of dunes may be a primary function of the parent material, particularly the content of clay. Without clay present, the process of rubefaction is inhibited and may even be prevented if the dune soils do not remain stable long enough to develop well defined profile differentiation. Increasing quantities of clay and carbonate effectively fix the dune form, ensuring its relative stability.

The contribution of windblown dusts forms an important constituent of the plains east of the main dunefields; some 2 m of fine grained sediment on the Gredgwin Ridge has originated in this way. An equivalent fine-grained component would have been contributed to the surrounding clay plains.

Finally, the area presents many striking examples of the influence of past hydrologic changes on landforms and ecosystems delicately adjusted to the controlling climatic regime. Throughout the past 100 years of intensive European settlement many changes have been initiated, some of which may prove irreversible. Careful planning is necessary to ensure the long-term protection of this region, the future value of which may involve land-use other than the present pastoral and agricultural activities. It is already proving to be one of growing importance for those who live in the sprawling urban centres of Adelaide, Melbourne and Sydney, centres that lie less than one day's drive from this most attractive semi-arid corner of southeastern Australia.

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REFERENCES

Blackburn, G., 1962. Stranded Coastal Dunes in North-Western Victoria. *Aust. J. Sci.* 24: 388-389.

Butler, B. E., 1956. Parna — an aeolian clay. *Ibid.* 18: 145-151.

———, 1958. Depositional Systems of the Riverine Plain in relation to soils. *Soil Publ. CSIRO Aust. 10.*

Butler, B. E., Blackburn, G., Bowler, J. M., Lawrence, C. R., Newell, J. W. & Pels, S., 1973. A Geomorphic Map of the Riverine Plain of South-eastern Australia. A.N.U. Press, Canberra.

Bowler, J. M., 1971. Pleistocene Salinities and Climatic Change: Evidence from Lakes and Lunettes in Southeastern Australia. In Mulvaney & Golson (Eds), *Aboriginal Man and Environment in Australia.* A.N.U. Press, Canberra: 47-65.

———, 1973. Clay Dunes: Their Occurrence, Formation and Environmental Significance. *Earth-Sci. Rev.* 9: 315-338.

———, 1976. Aridity in Australia: Age, origins and expression in aeolian landforms and sediments. *Ibid.* 12: 279-310.

Bowler, J. M., Hope, G. S., Jennings, J. N., Singh, G.

& WALKER, D., 1976. Late Quaternary climates of Australia and New Guinea. *Quat. Res.* 6: 359-394.

BOWLER, J. M. & POLACH, H. A., 1971. Radiocarbon Analyses of Soil Carbonates: an Evaluation from Paleosols in Southeastern Australia. In Yaalon, D. H. (Ed.), *Palaeopedology — Origin, Nature and Dating of Paleosols.* Intl. Soc. Soil Sci. & Israel Universities Press. pp. 97-108.

BOWLER, J. M., STOCKTON, E. & WALKER, M. J., 1978. Quaternary Stratigraphy of the Darling River near Tilpa, N.S.W. *Proc. R. Soc. Vict.* 90: 79-87.

CHURCHWARD, H. M., 1961. Soil Studies at Swan Hill, Victoria, Australia. *J. Soil Sci.* 12: 73-86.

———, 1963. Soil Studies at Swan Hill, Victoria, Australia. II. Dune Moulding and Parna Formation. *Aust. J. Soil Res.* 1: 103-116.

FIRMAN, J. B., 1965. Late Cainozoic lacustrine deposits in the Murray Basin, South Australia. *Geol. Notes, geol. Surv. S. Aust.* 16: 1-2.

GILL, E. D., 1973. Geology & geomorphology of the Murray River region between Mildura and Renmark, Australia. *Mem. natl. Mus. Vic.* 34: 1-97.

HILLS, E. S., 1939. The physiography of north western Victoria. *Proc. R. Soc. Vict.* 51: 297-323.

———, 1940. The lunette, a new landform of aeolian origin. *Aust. Geogr.* 3(7): 15-21.

———, 1975. *The Physiography of Victoria.* New Edition. Whitcombe & Tombs Pty Ltd, Melbourne, Australia.

LAWRENCE, C. R., 1966. Cainozoic stratigraphy and structure of the Mallee region, Victoria. *Proc. R. Soc. Vict.* 79: 527-553.

———, 1973. Explanatory Notes to Accompany Mildura 1; 250,000 Geological Map. *Vic. Geol. Surv. Report* 3.

———, 1976. The Murray Basin. In Douglas, J. G. & Ferguson, J. A. (Eds), *Geology of Victoria. geol. Soc. Aust. Spec. Pub.* No. 5: 191-198, 276-288.

MACUMBER, P. G., 1969a. Interrelationship between Physiography, Hydrology, Sedimentation, and Salinization of the Loddon River Plains, Australia. *J. Hydrol.* 7: 39-57.

———, 1969b. The Inland Limits of the Murravian Marine Transgression in Victoria, *Aust. J. Sci.* 32: 165-166.

———, 1970. Lunette Initiation in the Kerang District. *Min. Geol. J., Vic.* 6: 16-18.

———, 1978. Evolution of the Murray River during the Tertiary Period. Evidence from Northern Victoria. *Proc. R. Soc. Vict.* 90: 43-52.

PELS, S., 1969a. The Murray Basin. In Packham, G. H. (Ed.), *The Geology of New South Wales. J. geol. Soc. Aust.*, Vol. 16, Pt. 1: 499-511.

———, 1969b. Radiocarbon datings of ancestral river sediments on the Riverine Plain of southeastern Australia and their interpretation. *J. Proc. R. Soc. N.S.W.* 102: 195-198.

ROWAN, J. N. & DOWNES, R. G., 1963. A Study of the Land in North-Western Victoria. *Soil. Cons. Auth. Vic. T.C.* 2.

TWIDALE, C. R., 1972. Evolution of sand dunes in the Simpson Desert, Central Australia. *Trans. Inst. Br. Geogr.* 56: 77-109.

EXPLANATION OF PLATES

Plate 2

1. Vertical aerial photograph (a in Fig. 3) showing junction between cleared, cultivated linear dunefield in north and dark field of vegetated irregular to sub-parabolic dunes in the south. Compare dune forms with perspective diagrams, Figs. 5 and 6. Pale strip through irregular dunes in south-west represents a fire scar.

2. Vertical aerial photograph of the margin of Big Desert (b in Fig. 3). Dark vegetated siliceous dunes in north pass into subdued linear forms in the south developed on crests of NNW.-SSW. trending ridges one of which is marked by a dark strip of mallee woodland. A small lake basin and lunette have developed in the inter-ridge corridor.

North is at the top. Scale approx. 1:85,000. Crown copyright photographs by courtesy Director, Division of National Mapping, Canberra.

Plate 3

1. Vertical aerial photography of southern part of Outer Arumpo-Chibnalwood Lakes system set within the linear dunefield (d in Fig. 3). Broken line marks the shoreline of large freshwater lake (Outer Arumpo) with a pale lunette crest on the east. The outline of the inner saline deflation basins with steep gullied lunette ridges is defined by pale scalds.

2. Vertical aerial photograph of gypseous groundwater basin on the southern margin of Sunset Desert (c in Fig. 3). Irregular vegetated dunes in the north-west pass south into regular linear forms in the bottom left hand corner. In the centre a field of steep and high longitudinal siliceous dunes represent a form often found near the transitional zone between irregular and regular, subdued forms. The linear dunes have transgressed to the east across saline gypseous flats. Note their tendency to form Y-junctions. White areas represent small salt encrusted groundwater discharge sites within a formerly larger lake.

North is at top of page. Scale approx. 1:85,000. Crown copyright photographs by courtesy Director, Division of National Mapping, Canberra.

Plate 4

1. Vertical aerial photograph from Willandra Lakes region (e in Fig. 3) illustrating a vegetated sand plain with poorly defined dune ridges in the west. The plain is truncated on the east by the cliffed westerly margin of Lake Mulurulu.

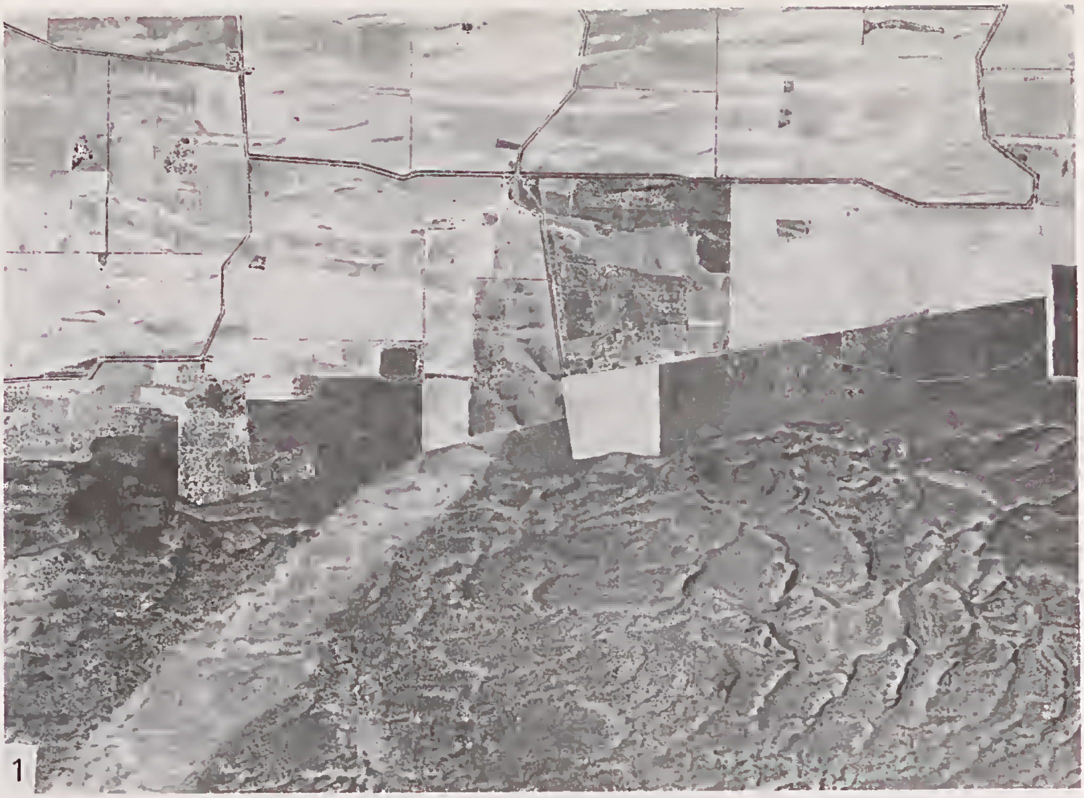
2. Vertical aerial photograph of area east of Rainbow, Victoria (f in Fig. 3), showing set of NNW ridges with sandy crests. Clay-rich swales are overlain by a thin surface sand cover giving rise to the unit mapped as 'clay plain with sand cover'.

North is to the top. Scale approx. 1:85,000. Crown copyright photographs by courtesy Director, Division of National Mapping, Canberra.

Plate 5

Vertical aerial photograph of the Murray River at Lake Victoria (g in Fig. 3) with river flowing in tract of low level alluvium with extensive scroll bars, oxbow swamps and distributary channels of Rufus River and Frenchmans Creek. In the south a belt of high level alluvium, with a surface patchwork of whitish scalds, stands as a terrace above younger alluvial deposits. In the north, the Lake Victoria basin is bounded on the west by linear dunefields and on the east by a sandy lunette (see Gill 1973).

North is to top of photograph. Scale approx. 1:85,000. Crown copyright photograph by courtesy, Director, Division of National Mapping, Canberra.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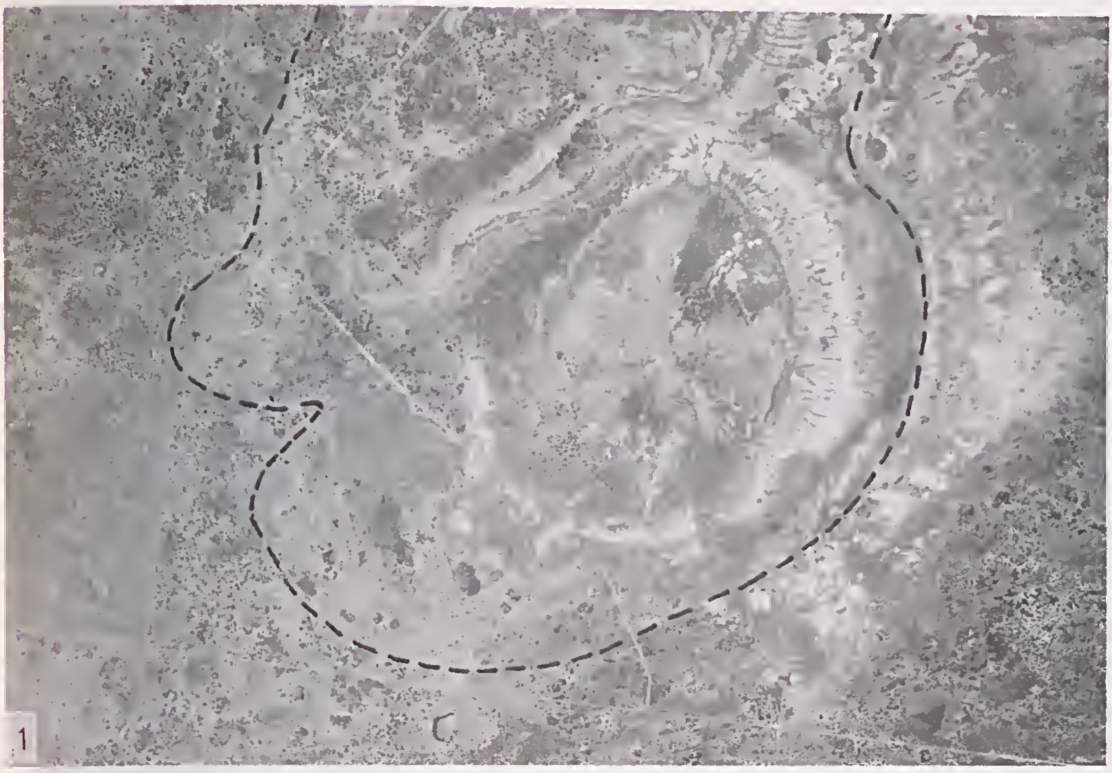

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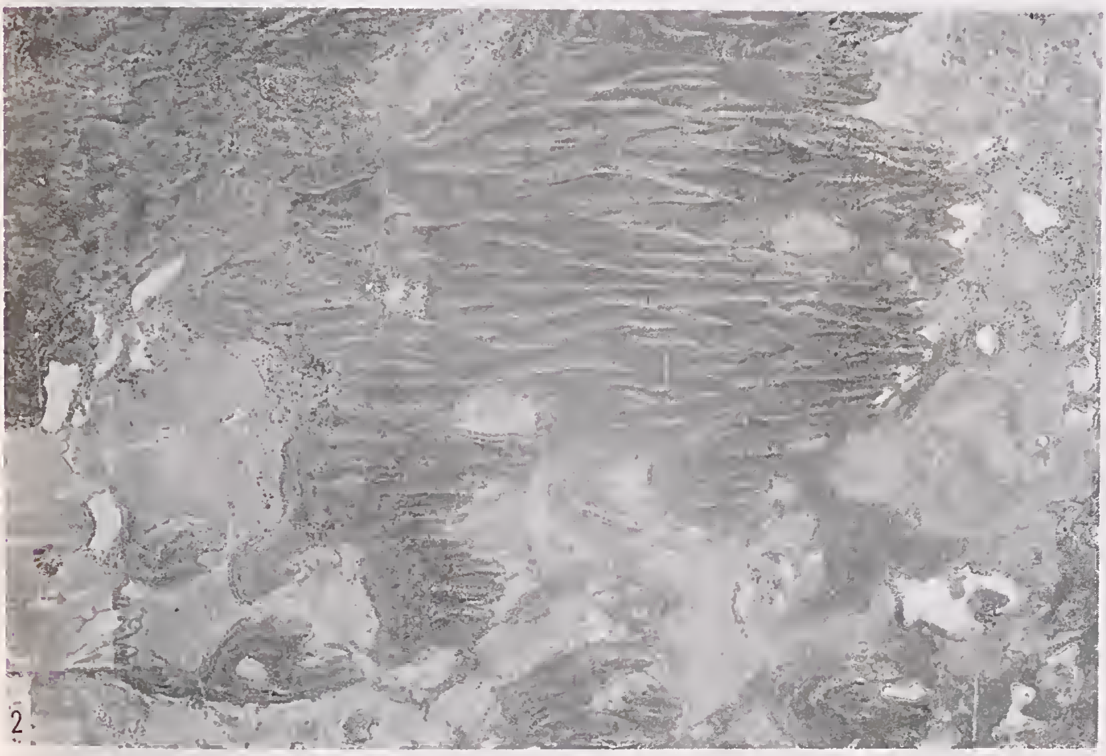

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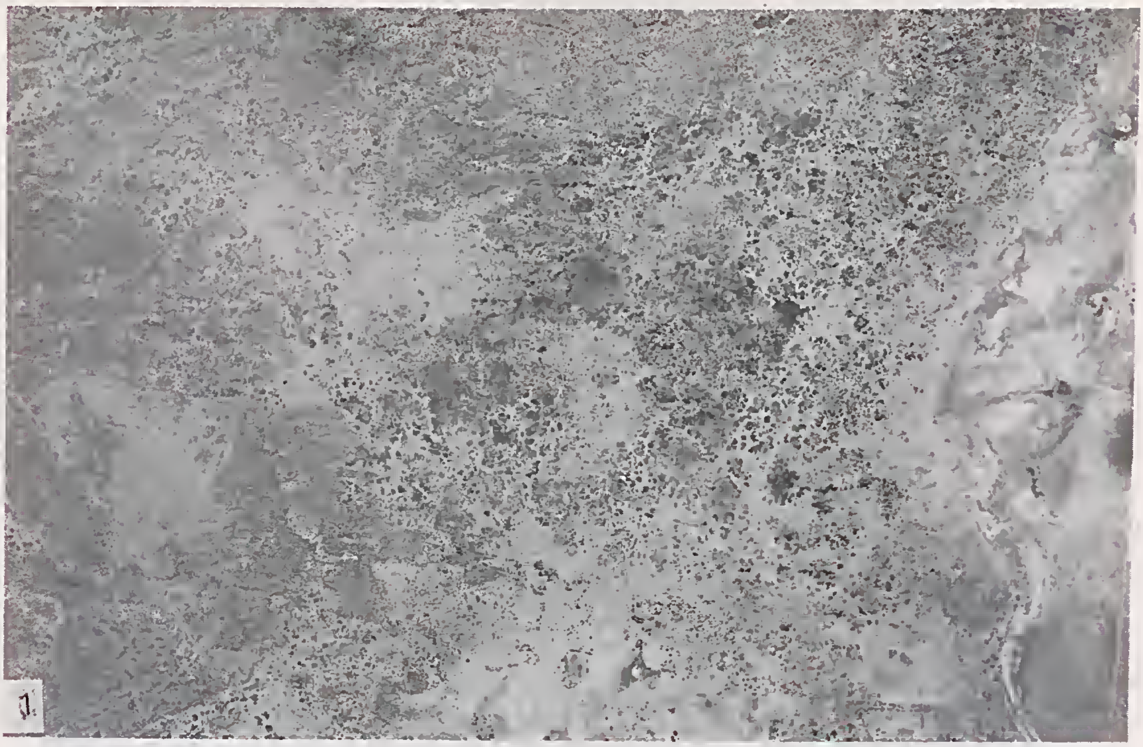

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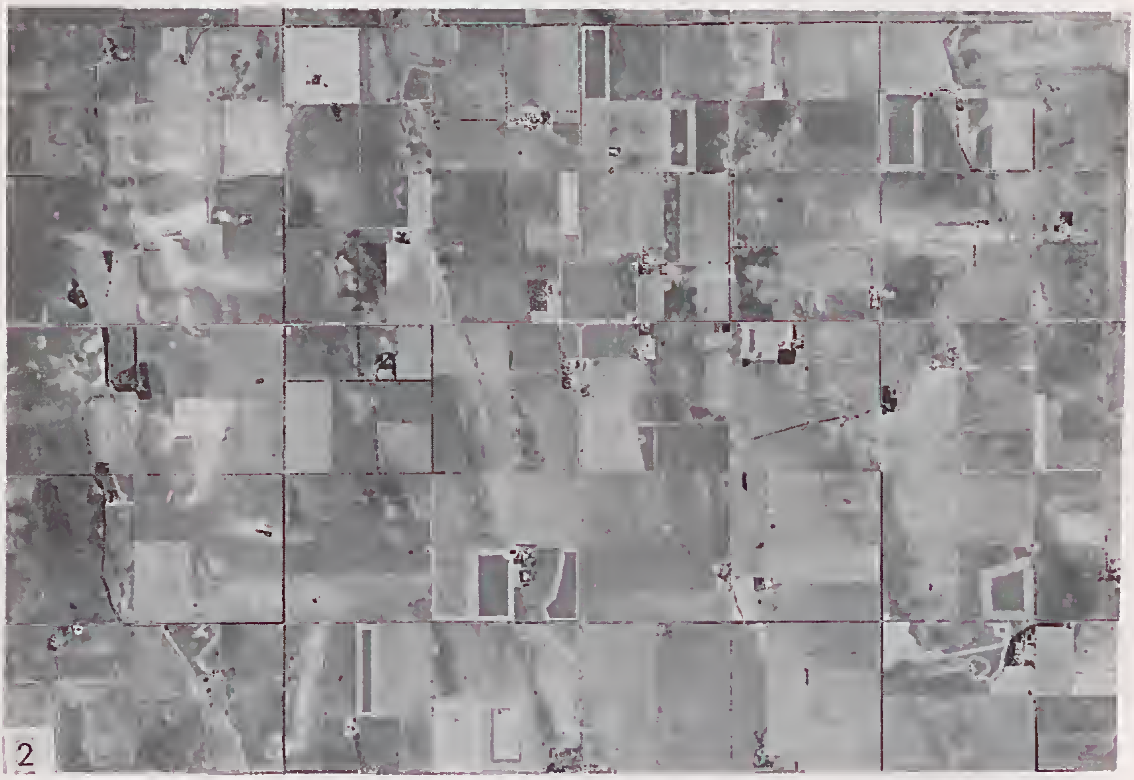

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